PIP-II power couplers cleaning and RT RF power tests

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(for coupler team)

PIP-II Technical Workshop

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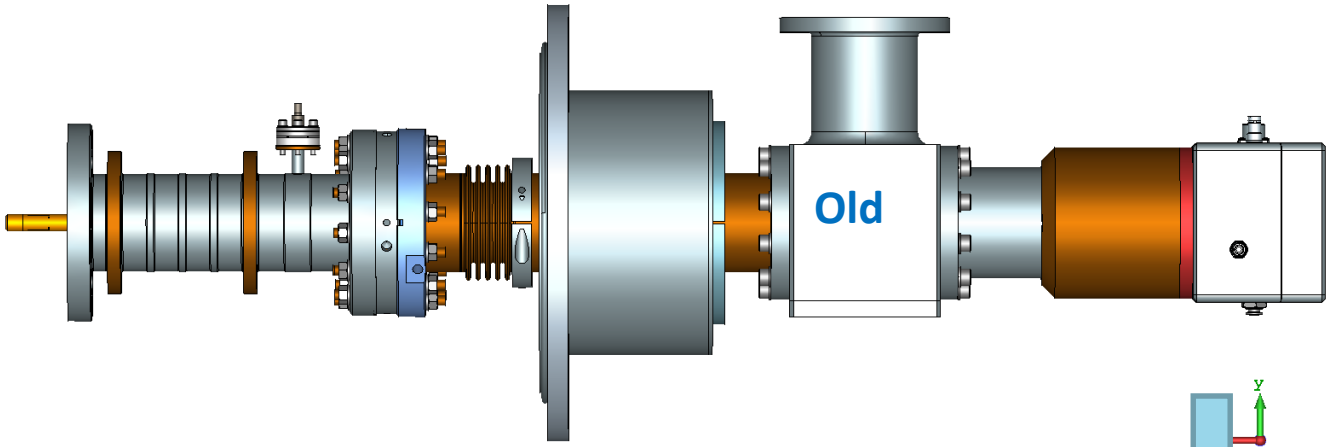
In partnership with:
France/CNRS/IN2P3 - IJCLab
India/DAE - BARC

Agenda

- SSR1/SSR2 coupler
  - Designs, acceptance and cleaning
  - Test statistics
  - Current status

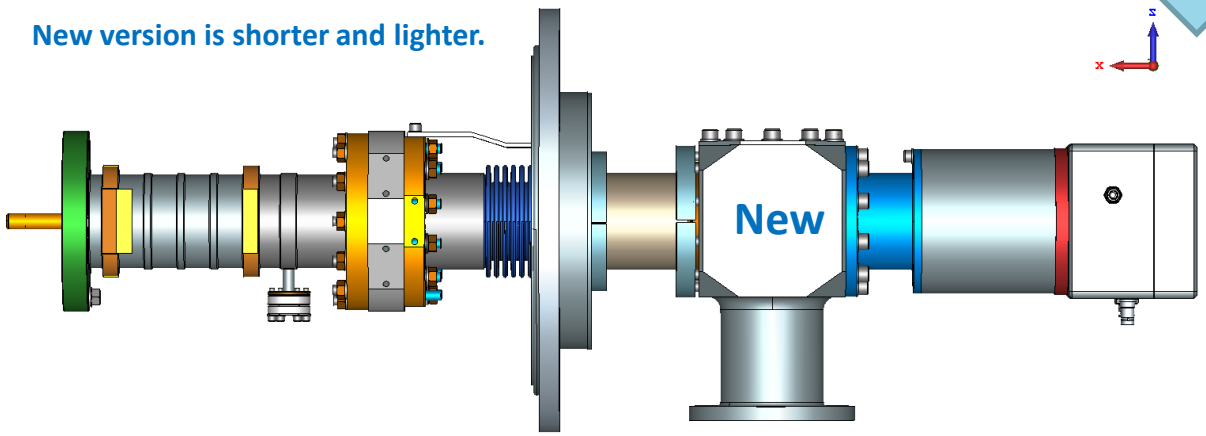
- 650 MHz coupler design for LB650/HB650
  - Coupler Prototypes and final design
  - RF test results for 2 types of prototype (A & B)
  - Summary

SSR1/SSR2 coupler design



"SSR1 prototype design", 17 couplers build and tested, 8 was assembled in SSR1 prototype CM (PIP@2IT)

New version is shorter and lighter.



"SSR2 prototype design", 8 in production:
4 - FNAL/CPI
4 - IN2P3/PNB

New design was made based on experience with prototype couplers

SSR1 cold-end couplers: processing/qualification

RF conditioning at room temperature

- Visual inspection and leak check
- Cleaning and installation of the vacuum end assembly on the RF test stand in cleanroom
- 120C baking 48 hours
- Testing up to specified power (10kW) in full reflection to check the structural performance of the ceramic window.
- During the test we check the RGA scan to monitor the emission of undesired substances (i.e. hydrocarbons) from the antenna.
- All activities of assembling/disassembling take place in the cleanroom

Fully integrated test at cold temperature

- After qualification at room temperature, the vacuum-end coupler is cleaned, installed on the jacketed cavity in class 10 cleanroom and undergo to 120C baking 48 hours

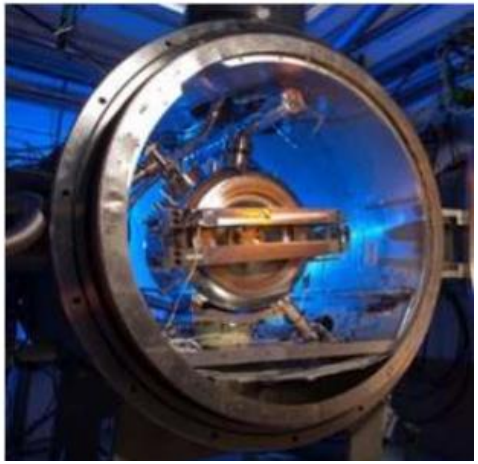
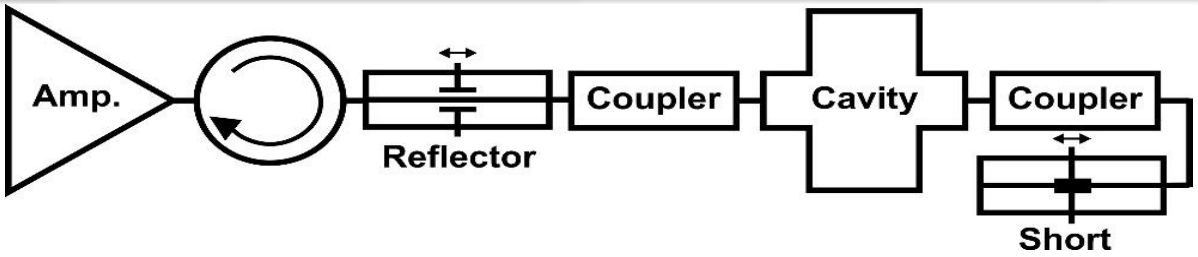
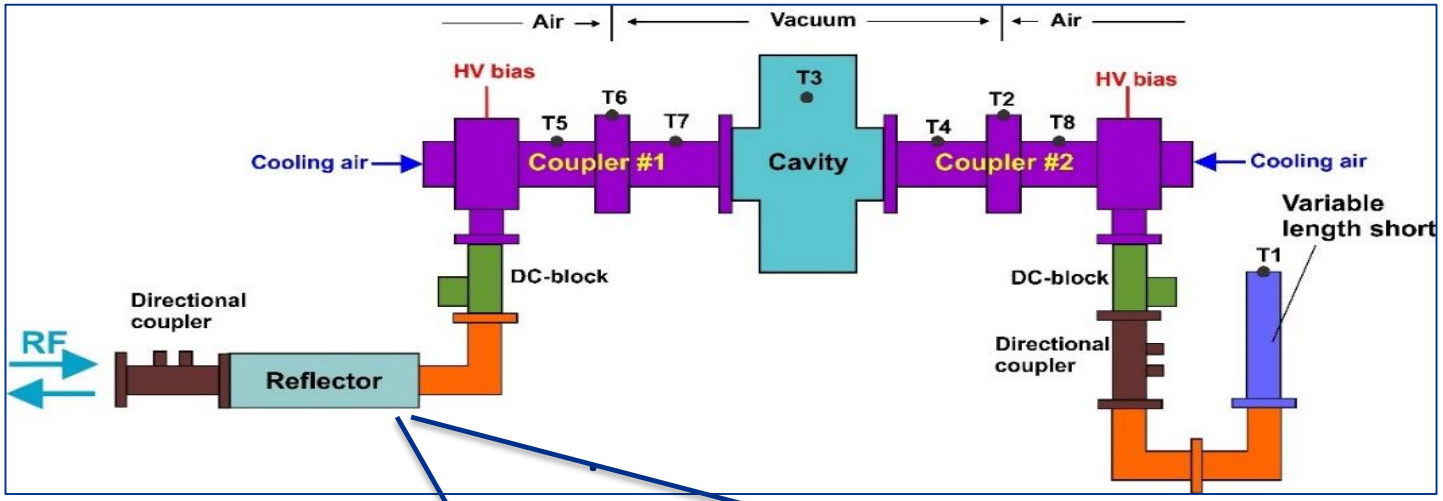
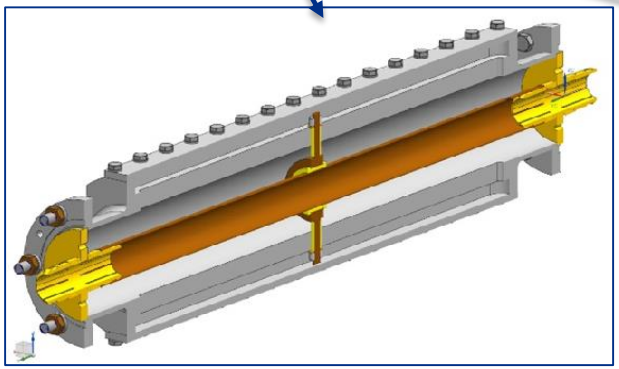


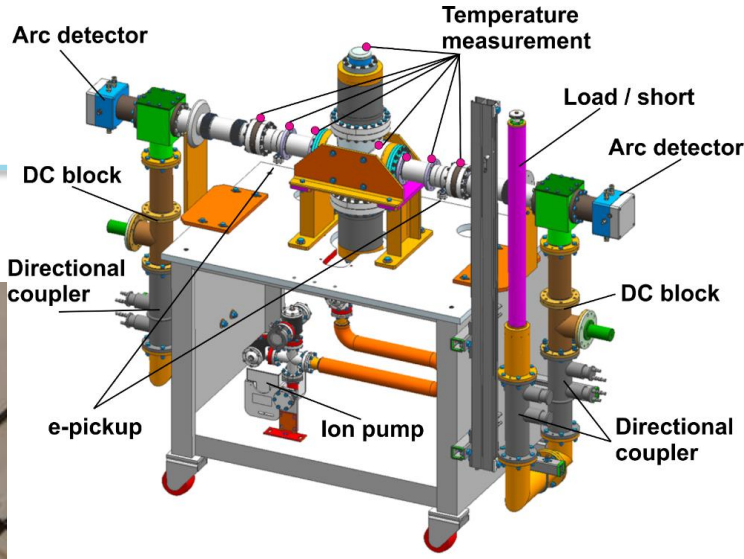
Diagram of RT test stand for testing 325 MHz couplers



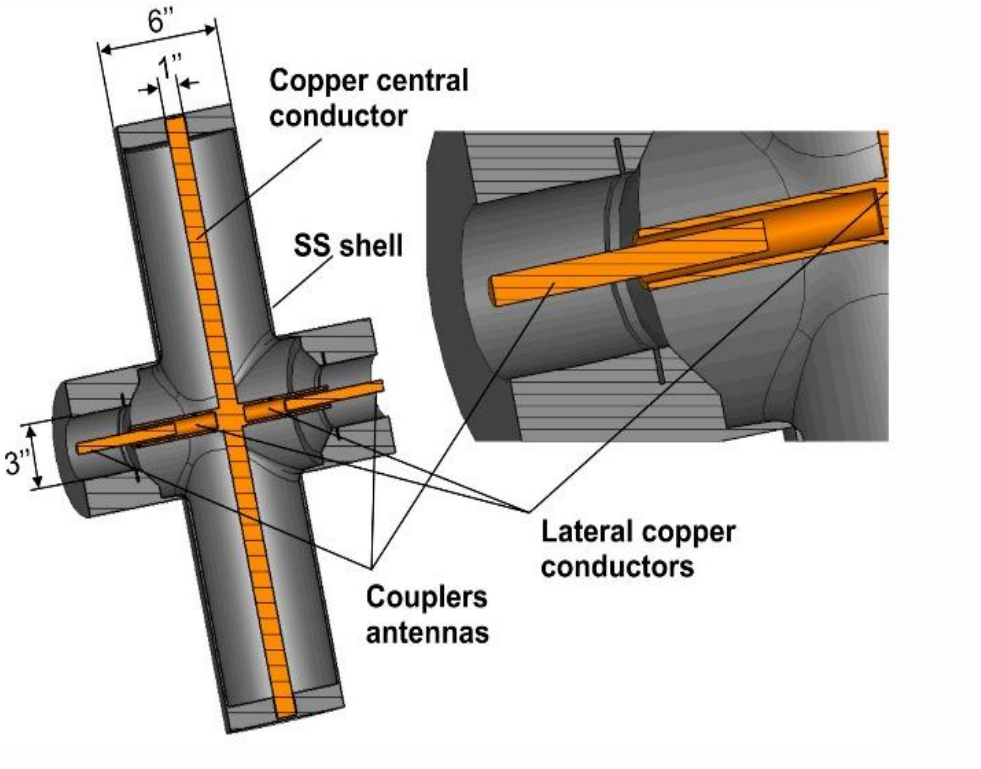


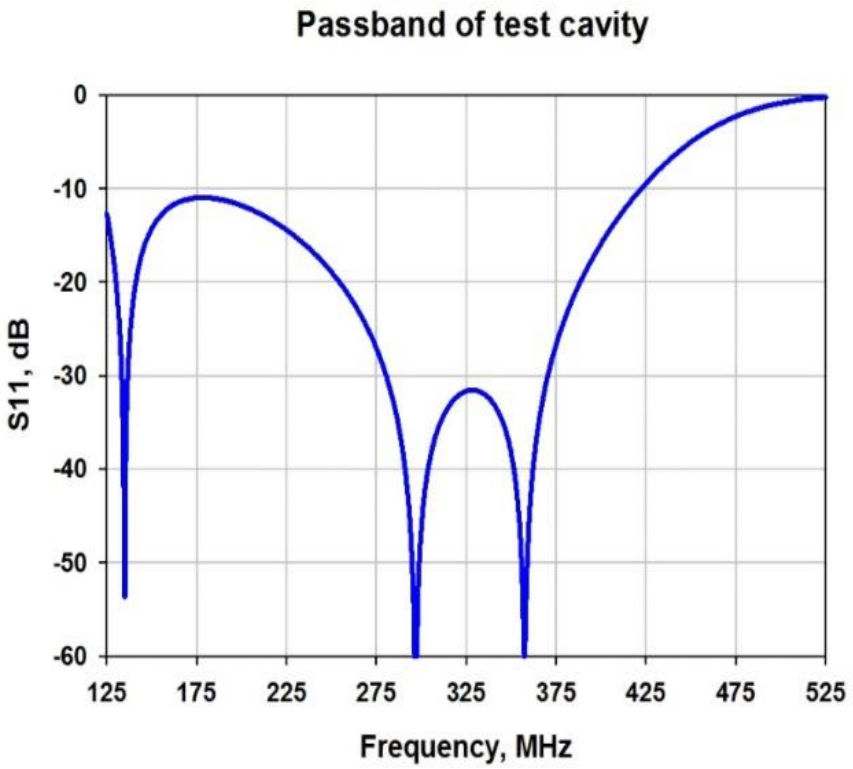


325 MHz coupler test stand



Antennas coupling in test stand (coupling chamber)



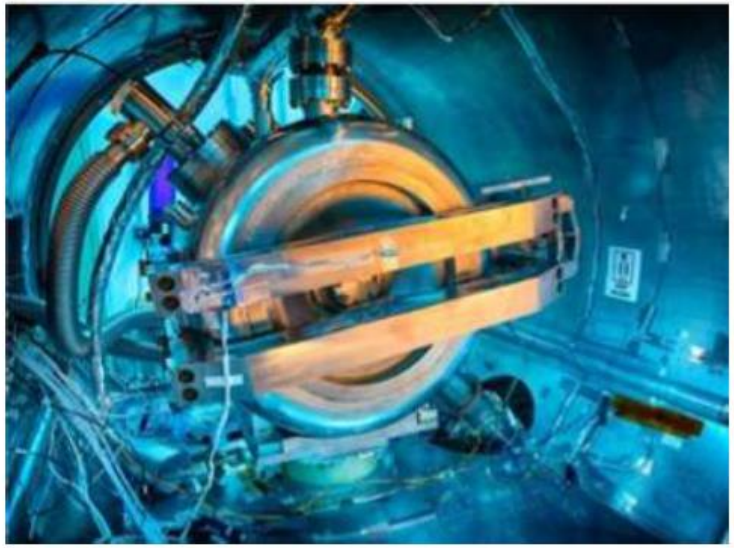


Results of testing at room temperature test stand.

Total number produced and tested couplers is 17 (CPI/Coorstek/MEGA). Tests were done at CW mode with full reflection. The reflection phases were changed with 90 degrees step, totally 4 phases were tested for each pair of couplers. Test was considered as completed if couplers sustain more than 1 hour at each phase point at maximum power. Results of testing is presented at table. Test shows that multipactor can be successfully suppressed by DC bias with voltage ≥ 3 kV. No attempts to do processing without DC bias.

RF power	Number of tested couplers	Number of failures couples	Reason of failure
10 kW	17	0	
20 kW	5	1	Low quality ceramic.
30 kW	2	0	
47 kW	2	1	High power.

SSR1 coupler checkout in STC tests



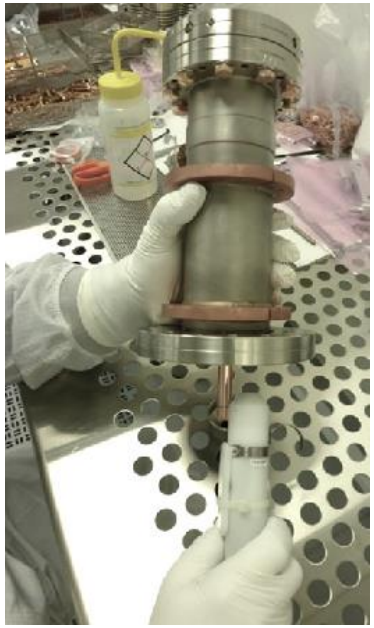
Coupler performance was checked out in STC SSR1 integrated tests:

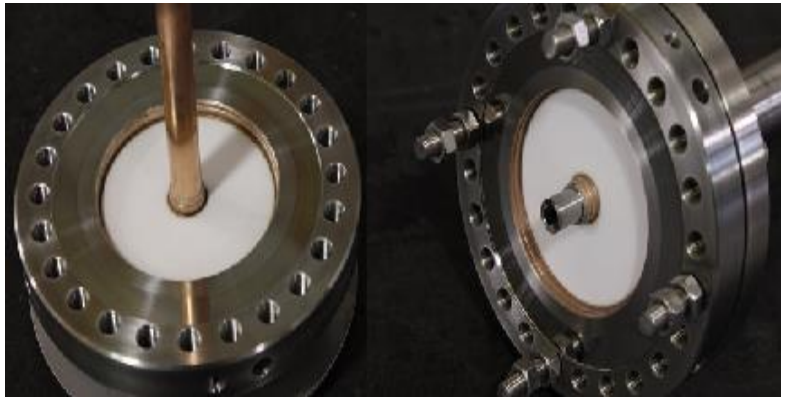
- Total number of SSR1 cavities with couplers tested - 10
- At 2K, cavity tuned off-resonance, HV bias 4kV on coupler, 4 SCFM air flow
- Forward power gradually increased to 5 kW (administrative limit for SSR1) in pulsed mode with duty factor 2% (20 Hz pulse rep. rate, 1ms pulse duration), dwelled at maximum power for 15 min, making sure that there no FEP, PMT and vacuum activity, no bias current/voltage spikes/dips
- Repeat with 4%, 8% and 15% DF (2ms, 4ms and 7.5ms)
- Repeat in CW mode

Courtesy of A.Sukhanov

Proto SSR1 CM assembly

- Eight qualified couplers are installed in SSR1 prototype CM.
- SSR1 CM under testing @PIP2IT. Some coupler heating data are available for analysis.



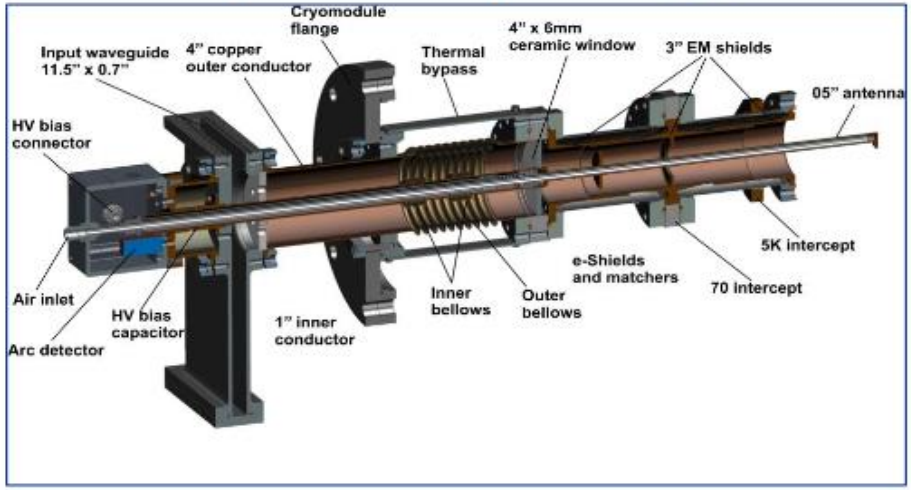


Current status of SSR couplers:

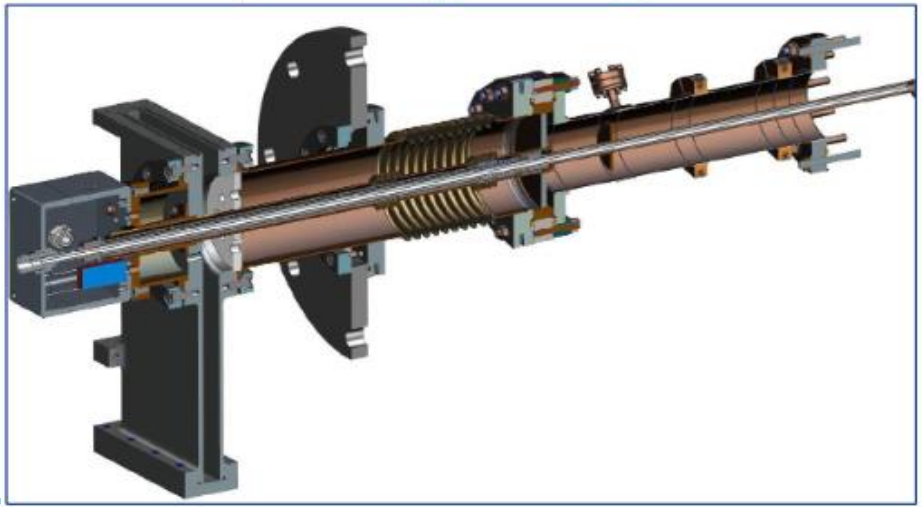
- Four SSR2 couplers will be produced by CPI and four coupler will produced by French colleagues (procurement awarded).
- All couplers are supposed to pass trough high power acceptance test at room temperature test stand. **Acceptance criterium is successful operation at power level 12 kW, CW, full reflection (requirements for SSR2 coupler).**
- “Successful operation” is to stay at each reflected phase point (4-8 pints) for 1-2 hour (to reach thermal equilibrium).
- Cleaning, baking, RGA scan at vendor. Fermilab will assembly cold parts for RF tests at clean room, bake 120C/48hrs. After RF test coupler will be disassembled in clean room and put on vacuum manifold. For prototype series procedure can be different.

Two type of prototypes were designed, built and tested

650 MHz coupler without copper coatings (with EM shields):



650 MHz coupler with copper coatings



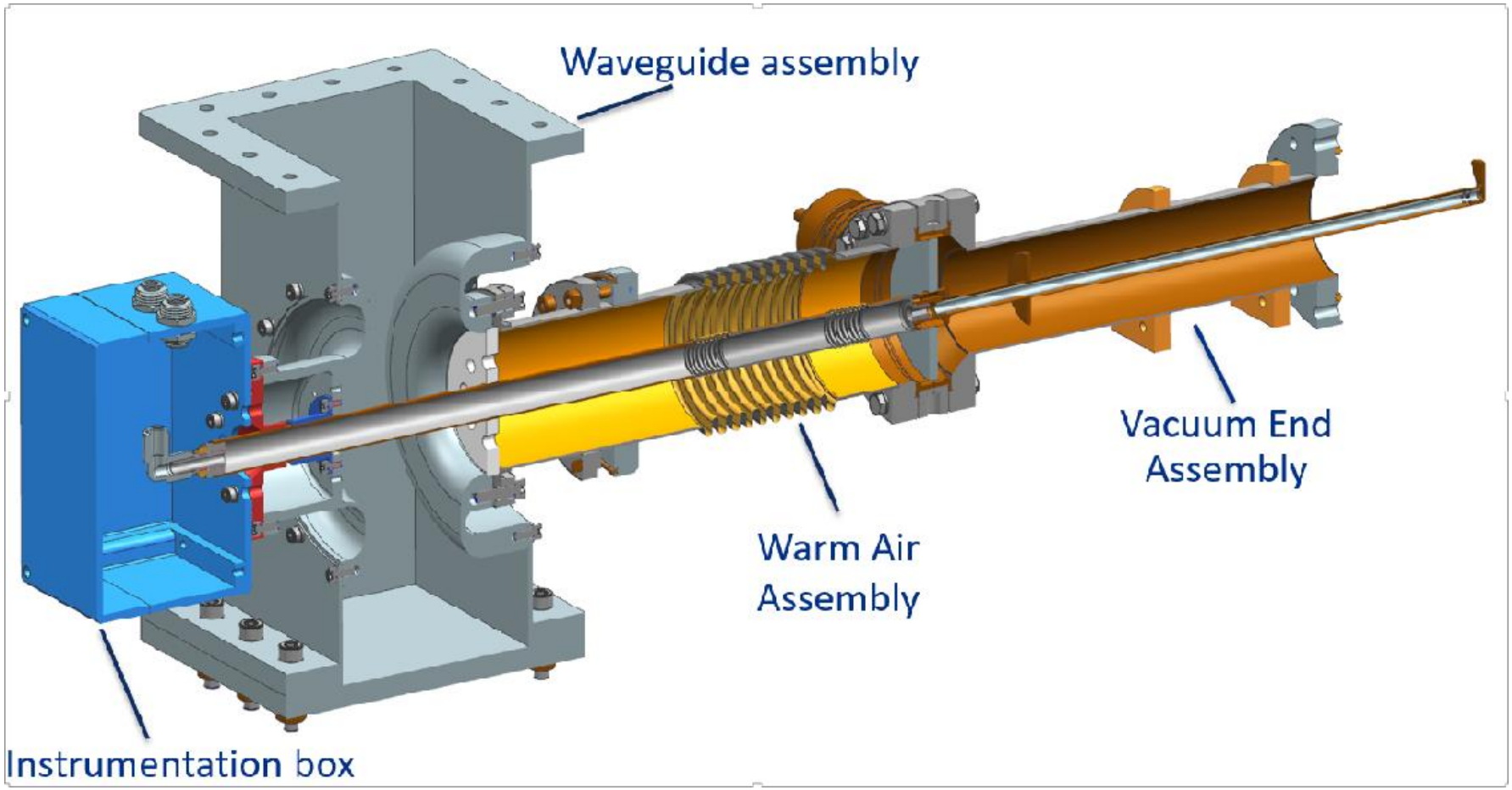
Vacuum parts of couplers:

a) copper coated

b) with EM shields

New design of 650MHz coupler based on prototype experience

Coupler Assembly F10056895



650MHz Coupler Testing Requirements (ED0010867)

- The maximum power delivered by HB650 cavities to the beam is about 43 kW at 2 mA beam current with ~20% reflection.
- Considering an additional allowance for microphonics compensation and coupling mismatch and assure operational reliability with suitable overhead coupler shall be tested and qualified at 50 kW input RF power with full reflection and arbitrary reflection phase (see PIP-II TRS). The total propagating power (forward + reflected) inside the coupler will be 100kW.

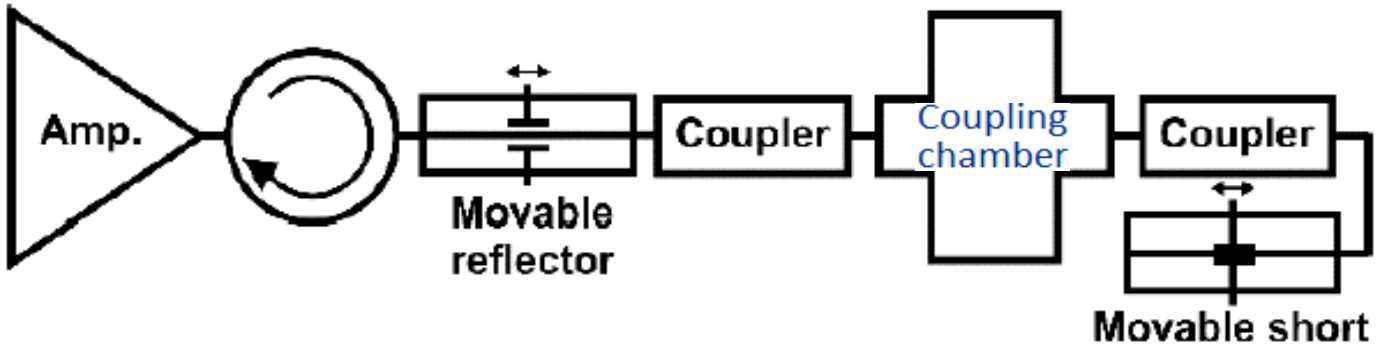
Testing Protocol for 650 MHz couplers (repeated 4 times for each phase point).

- Pulse length 10ms, Power ramp 0 => 100 kW, Rep.rate 1 Hz (max. aver. power 1 kW)
- Pulse length 100ms, Power ramp 0 =>100 kW, Rep.rate 1 Hz (max. aver. power 10 kW)
- Pulse length 650ms, Power ramp 0 => 80 kW, Rep.rate 1 Hz (max. aver. power 52 kW)
- Pulse length CW, Power ramp 0 => 50 kW, after that stay 2 hours at 50kW.

**Note: The pulse length in each step may vary depending of outgassing activity during processing.*

HV bias +4 kV (adjustable up to +5kV maximum) to suppress multipactoring.
Air flow should be above 10 SCFM (standard cubic feet per minute), typical value 23 SCFM (5 g/s).

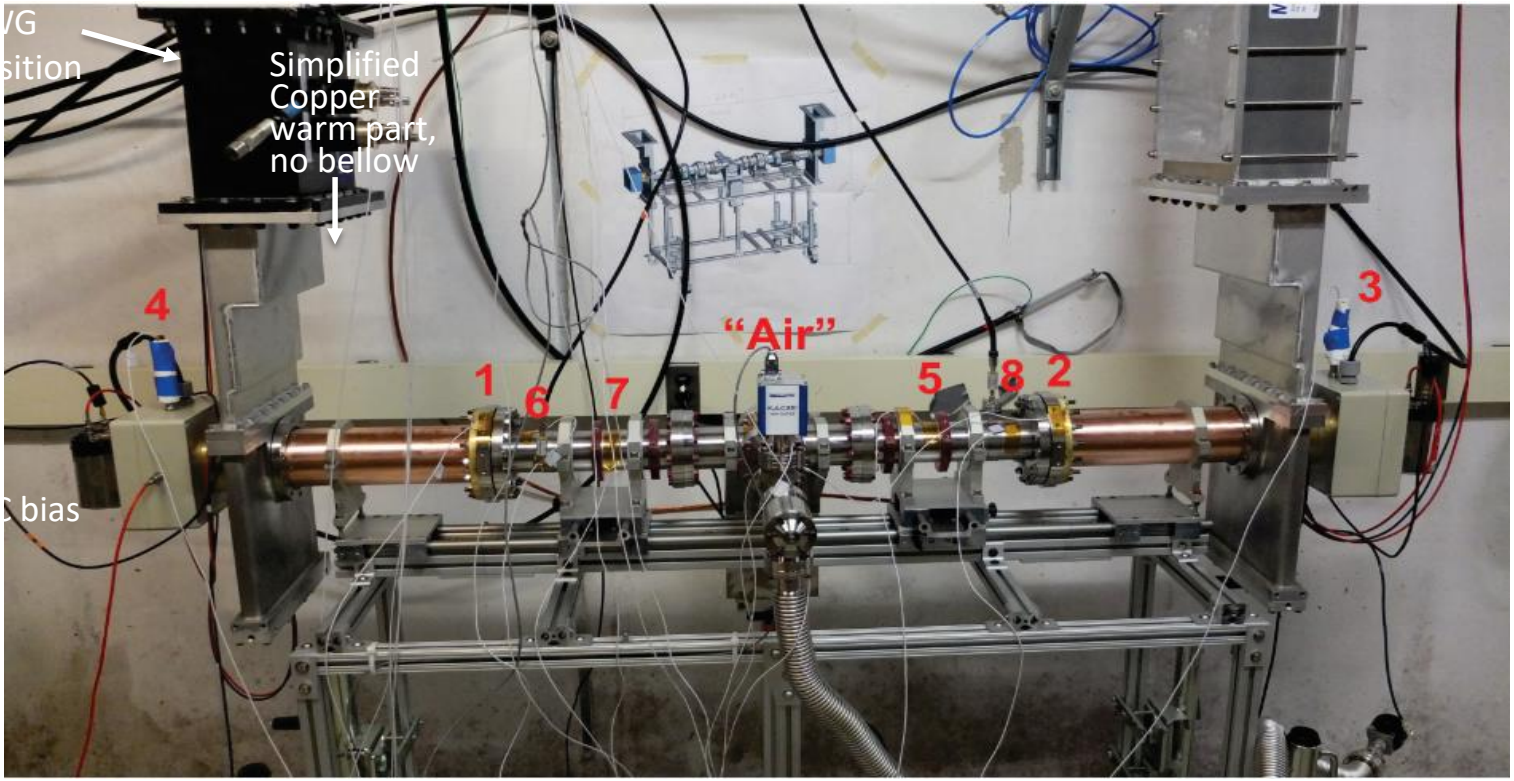
Coupler Test stand schematic and RF power



Power source used for the coupler test is IOT with maximum CW power 30kW. Power available for the coupler test ~100kW obtained due to resonance conditions between movable reflector and movable short (amplification x 5-7)

Test stand configuration

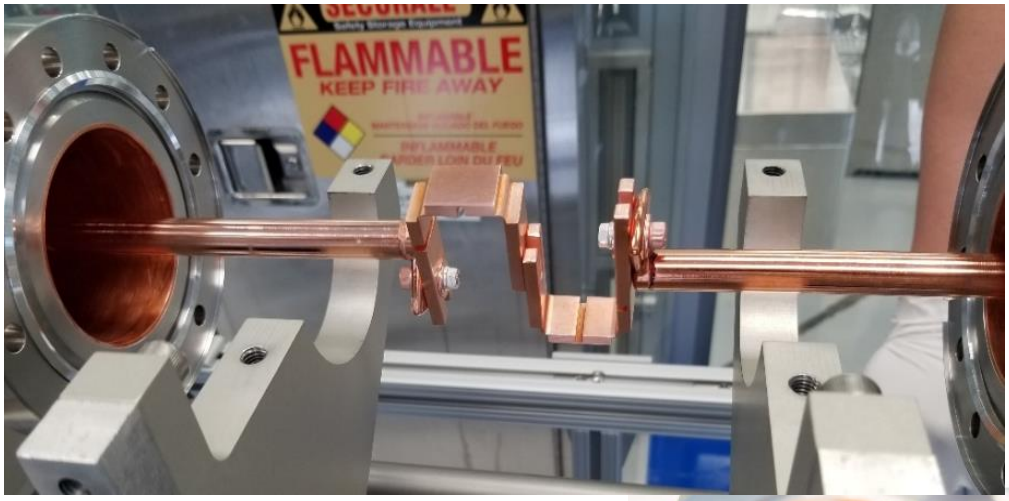
- *Assembled with chamber in the clean room. Antennas connected by bridge made of multi-wire (1st test) or solid copper (2nd).*
- *Vacuum assembly leak checked and baked at 120°C 48 hrs. Warm parts connected at test stand later.*
- *In first test the simple copper tubes used (no bellows). Later we use designed parts.*



Temperature sensors:

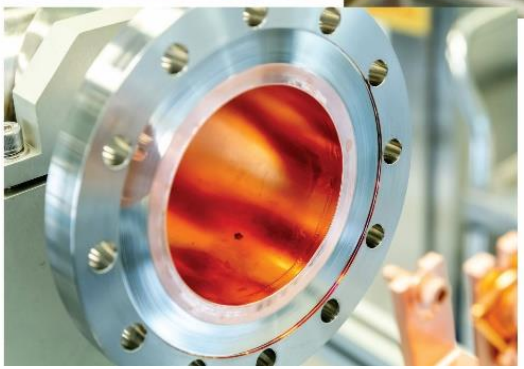
RF window (1,2); 5K intercept (5,6); 50K intercept (7,8); Air outlet tube (3,4); chamber ("Air").

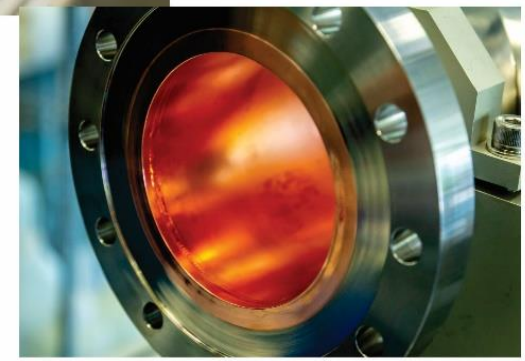
Antennas inter-connections



Connection between antennas before tests

After tests
Everything looks OK



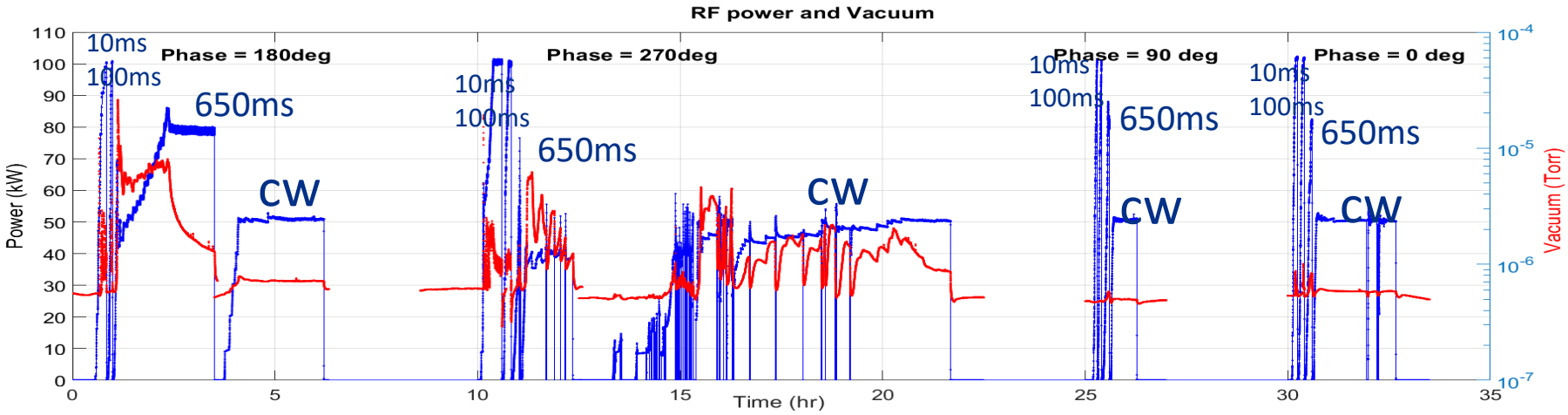


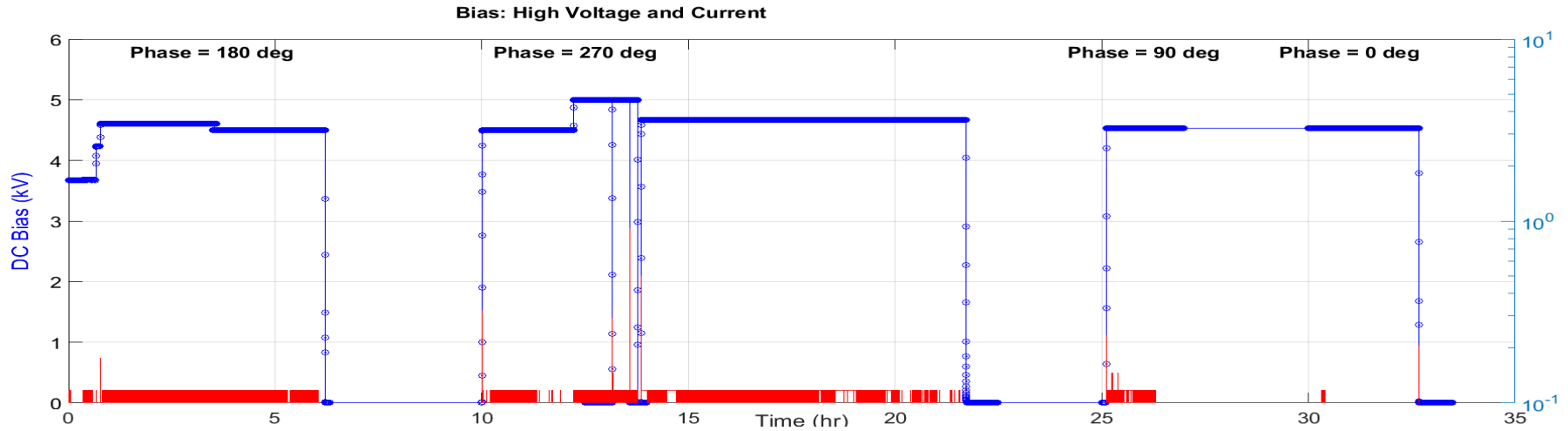
Testing history

- Prototype B (conventional):
  - **Test#1** (antennas connected with multi-wire bridge).
    - Slow processing (outgassing).
    - Achieved 50kW@90°, 32kW@180°, 28@270°, 3kW@0°.
    - Metallization on Cu plating surfaces
  - **Test#2:** (antennas connected with solid Cu bridge):
    - HP processing with DS;
    - Waveguide heating test

- Prototype A (EM shielded):
  - HP processing with DC (nominal)
  - DC polarity test
  - HP processing w/o DC bias
  - Test with nominal warm parts (SS copper plated with bellows)
  - Memory test

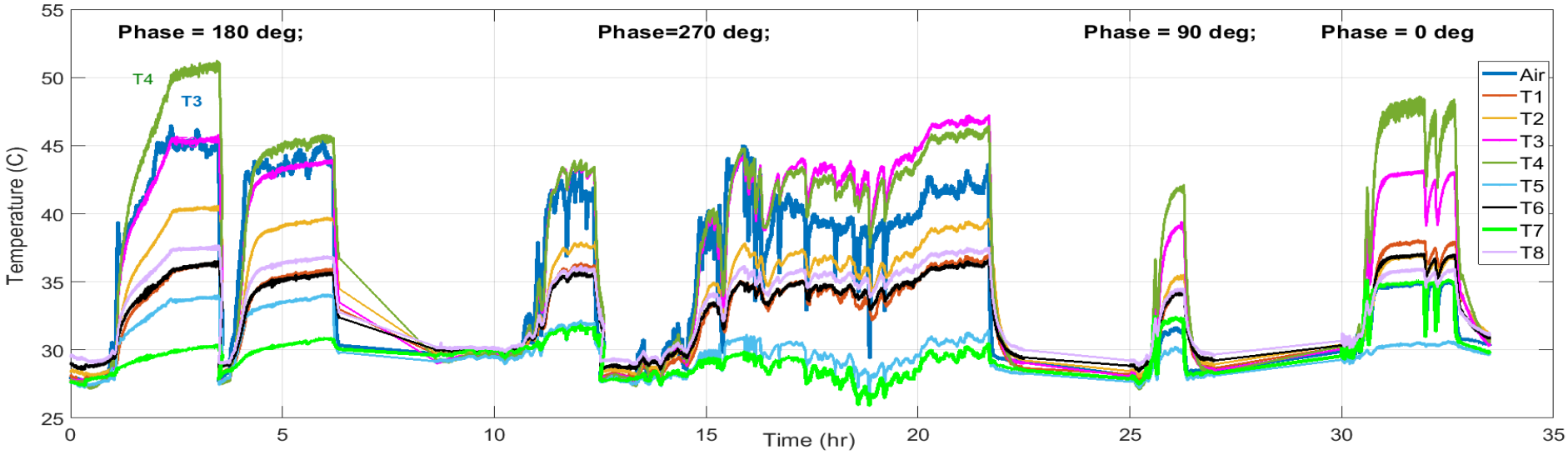
Test results for conventional design (prototype B)





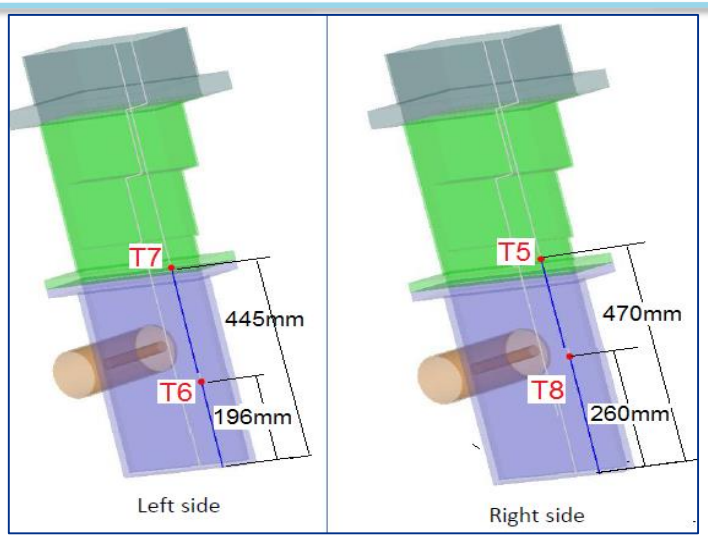
Fast processing at 90 and 0 degree phase, longer processing at 270 deg, no bias current

Temperature in coupler

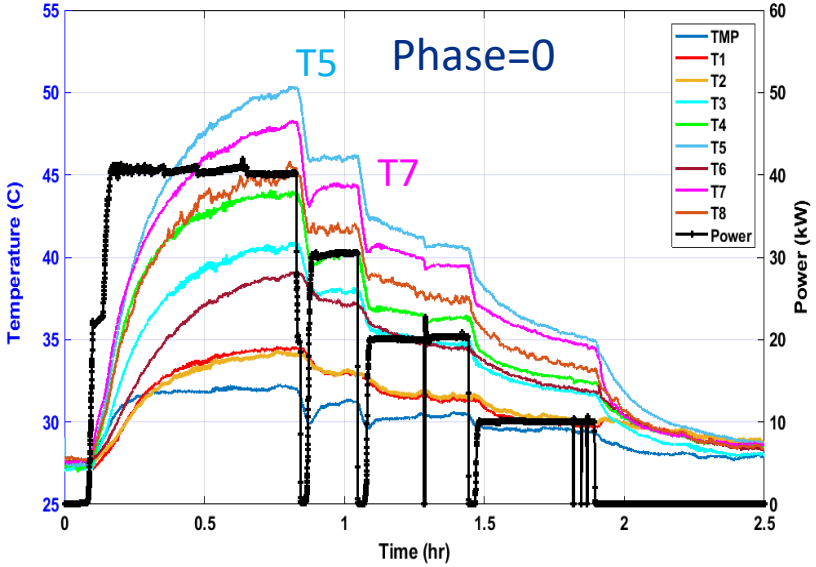


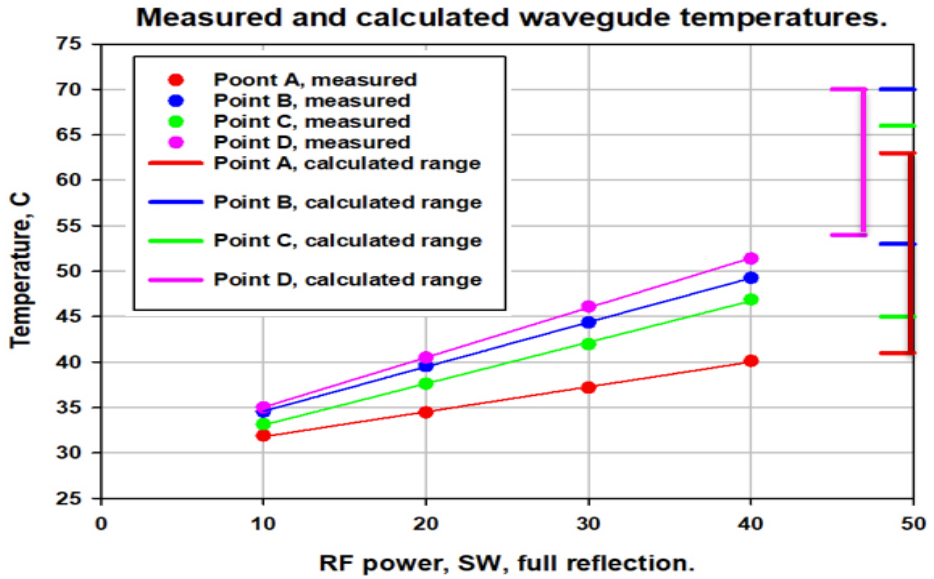
- Maximum temperature at air outlet tube (50°C)
- Temp signals show kind of mirror symmetry at 270 deg (T1=T2; T5=T7; T6=T8)
  → high fields in chamber and bridge area.
- Air flow ~5 g/s in each coupler

Waveguide heating test (narrow WG).



- Waveguide was heated during coupler tests.
- For comparison with simulation we tested temperature of waveguide for different levels of power in CW regime 10kW, 20kW, 30kW & 40kW.
- Reflection phase was 0 degrees in this test. For test all fans were switched off to provide pure convective cooling regime, short plate of the narrow waveguide was water cooled as designed.





Waveguide heating simulations

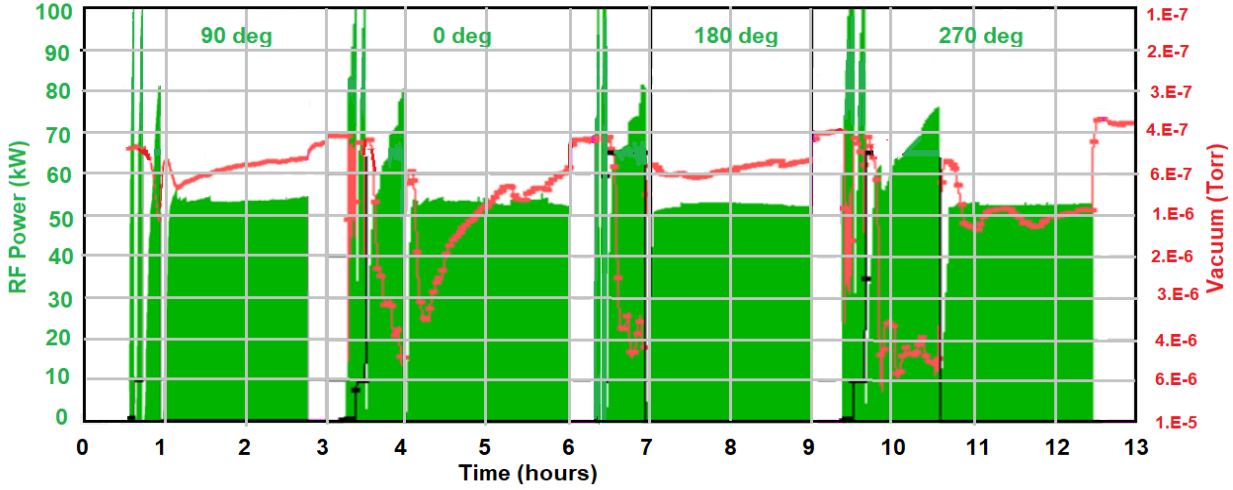
Power dissipation (W) and maximum temperature in the aluminum waveguide and adapter, convection cooling is assumed (simulation results).

	100kW, TW	50kW, 0°	50kW, 90°	50kW, 180°	50kW, 270°
Power dissipation in "narrow" WG, W	**199**	**78.7**	**245.3**	**314.5**	**148**
Power dissipation in current Adapter, W	**105**	**96.6**	**88.8**	**112.7**	**120.5**
Total power dissipation	**304**	**175.3**	**334.1**	**427.2**	**268.5**
Temp with water cooling	59 C°	51 C°	57 C°	68 C°	62 C°
Temp w/o water cooling	100 C°	66 C°	114 C°	137 C°	89 C°

To compare with 176 W and T_{max}=57 C° in standard WR-1150. Standard WR-1150 is used in new coupler design, no water cooling

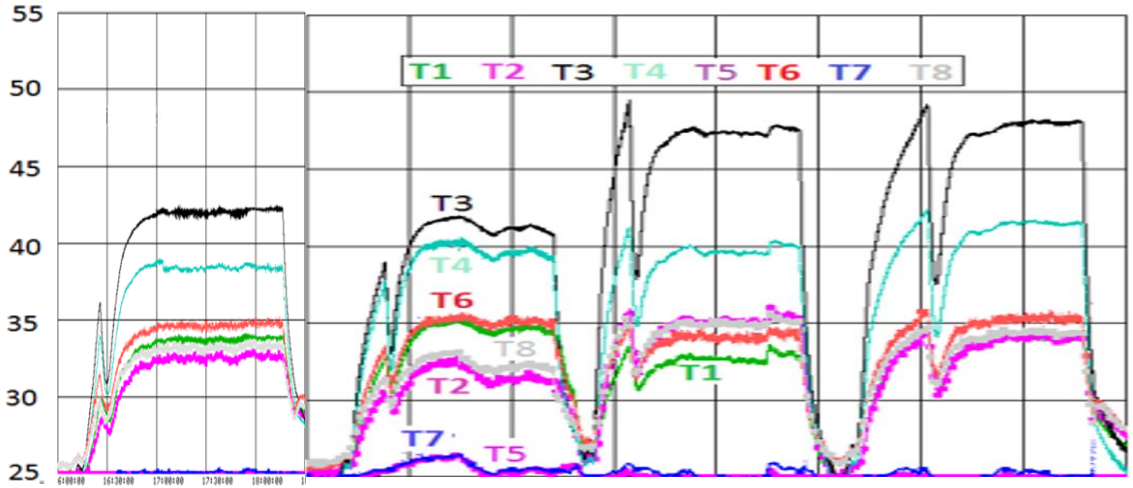
Coupler EM-shielded design (prototype A)-test with DC bias

RF power and Vacuum



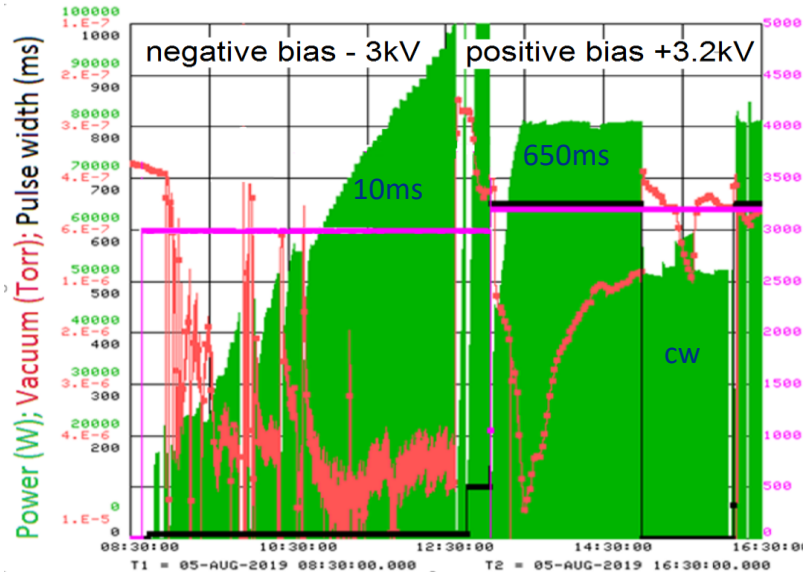
- HP processing history for EM shielded design for 4 different configuration for reflection: phases: 90; 0; 180; 270 degrees.
- DC bias 4-4.5kV.

Temperature (C) at different coupler locations

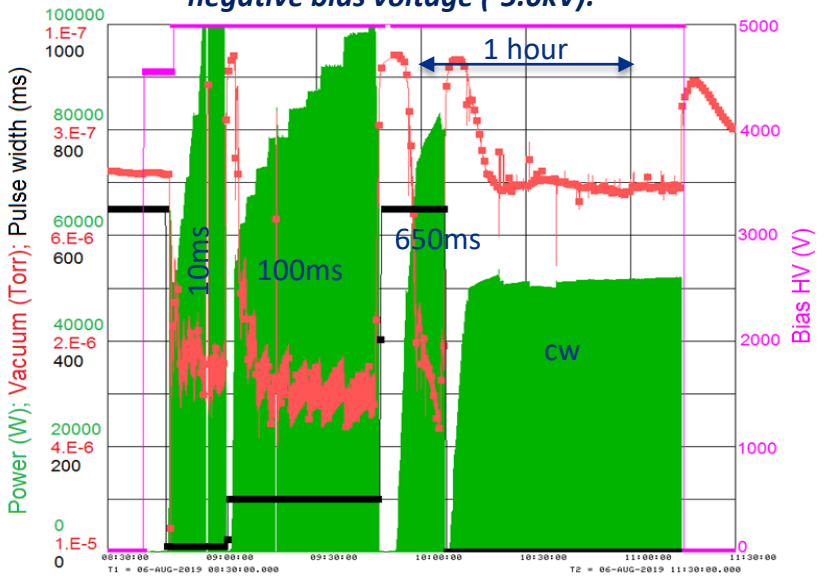


HV bias polarity test.

To understand effect of bias polarity on coupler performance the polarity was switched from positive to negative and processing was repeated using same protocol (270 deg phase).



negative bias voltage (-5.0kV).

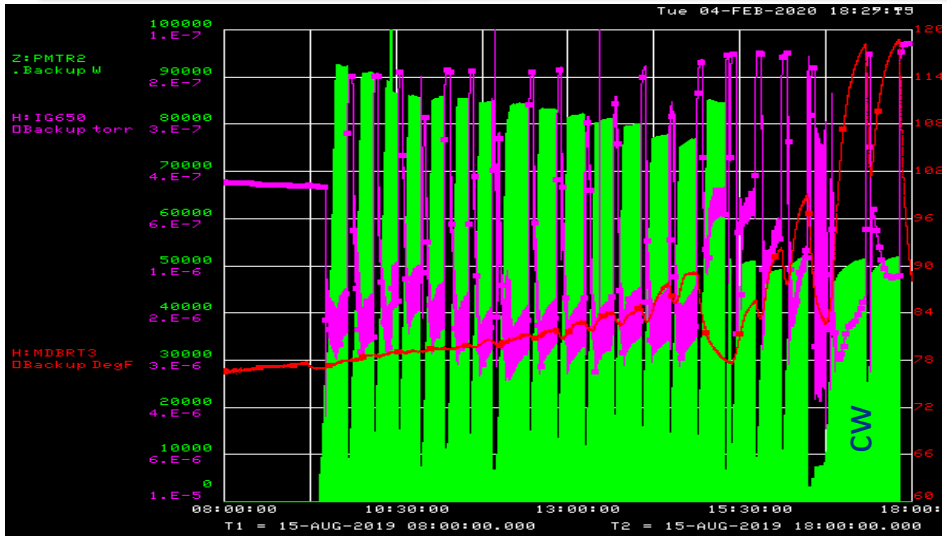


- Positive and negative 3kV bias was applied for short pulses (10ms) to compare the MP threshold.
- For negative polarity the MP activity starts at about 18 kW, while for the positive bias the threshold was moved to 50 kW power level. W/o bias MP starts at ~6 kW at full reflection.
- For negative polarity couplers were conditioned for ~ 4 hrs at 10 ms pulses ramping power up to 100 kW. The vacuum was ~ 4.E-6 Torr and signal noisy ('hairy'), which indicates that MP was not suppressed completely.

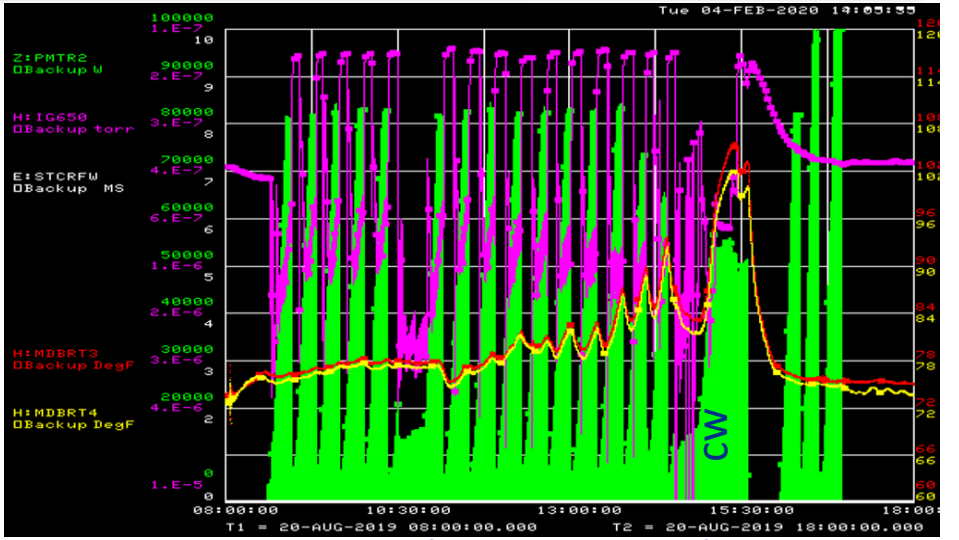
- For positive +3.2kV bias coupler was processed 4 hrs: 10ms, 100ms, 650ms and CW up to 50 kW. No any unusual vacuum activity, no MP for this polarity
- For negative polarity -5kV, processing is better, but still signature of MP on vacuum signal.

650 Coupler processing(v.A) without HV bias

Green-power(W)
Magenta-vacuum
Yellow/Red-Temp



270 deg

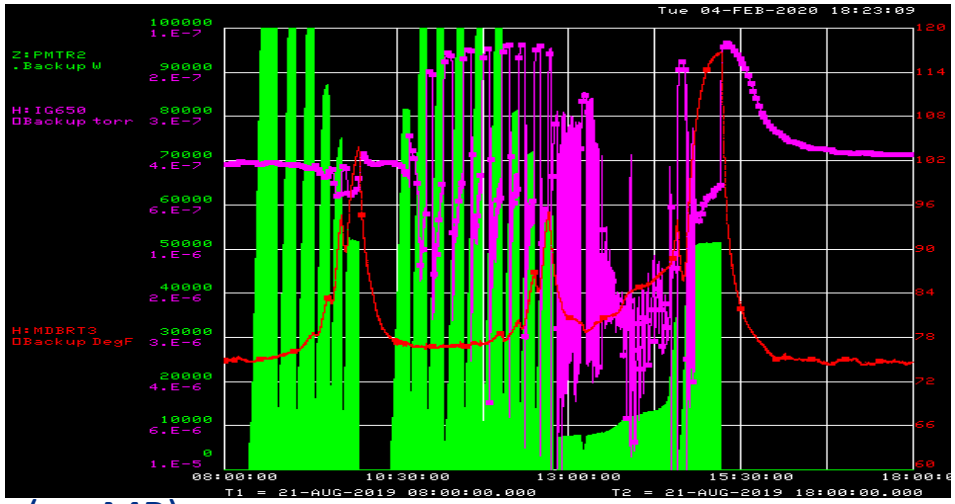


0 deg

90 deg

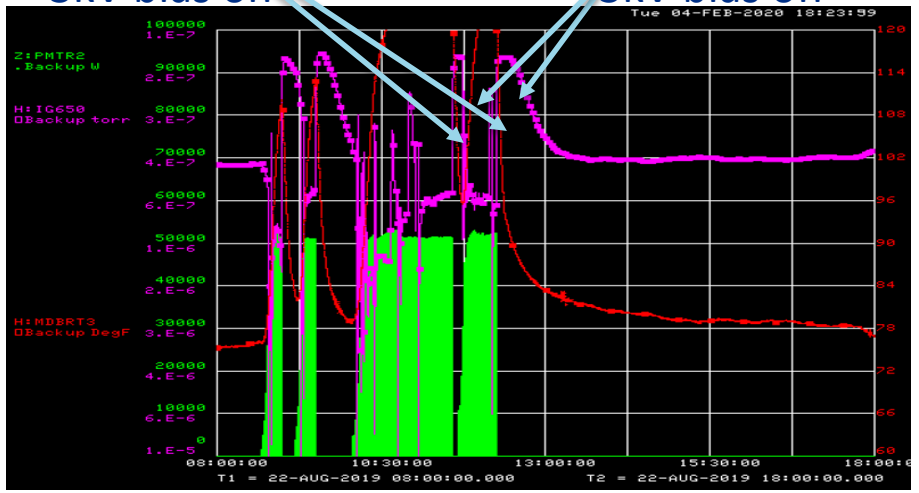
+3kV bias on

+3kV bias off



(no MP) 90 deg

180 deg



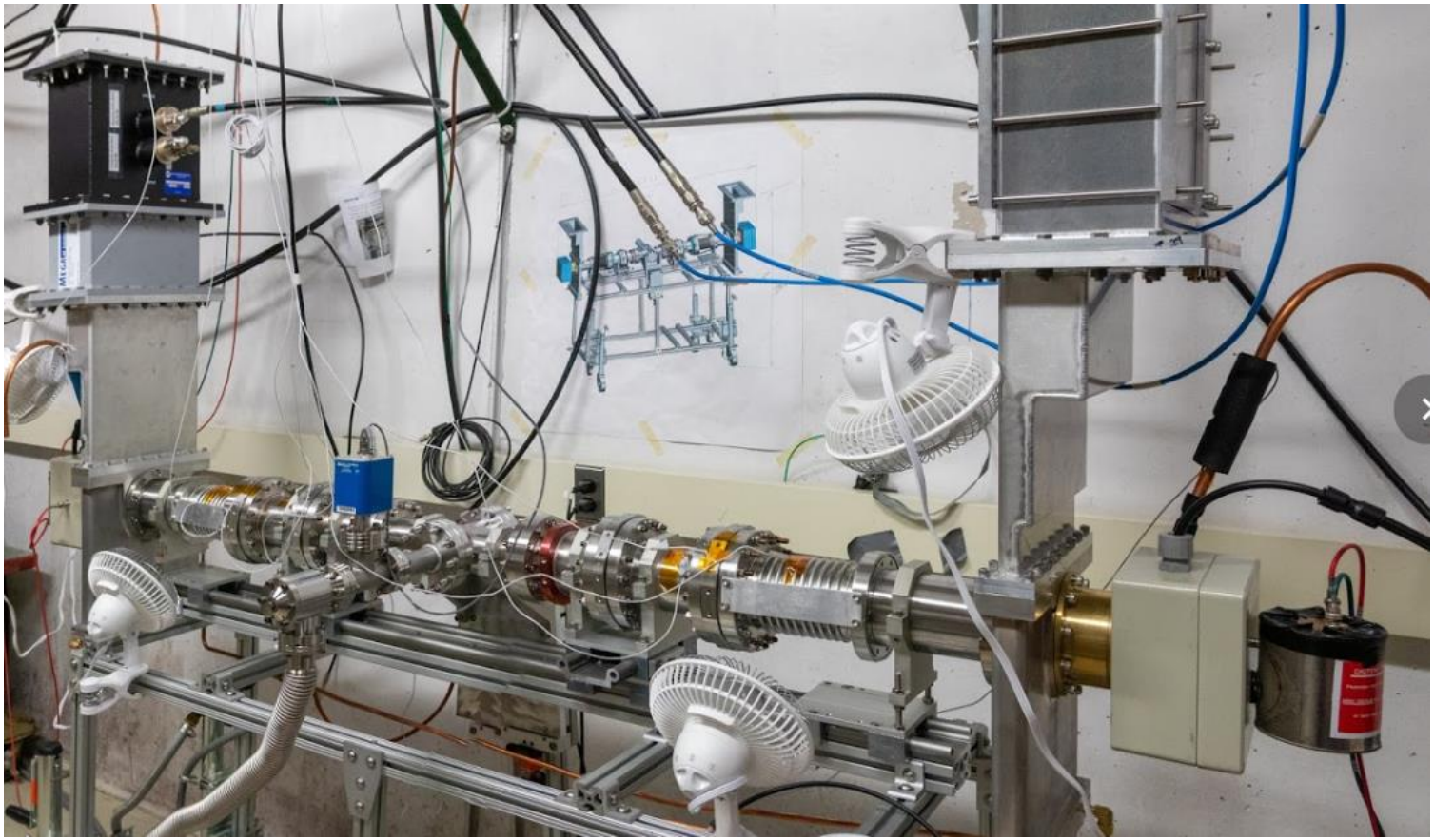
180 deg, 50kW, CW

RF conditioning w/o HV bias for EM shielded coupler

Results and conclusion:

1) Couplers were conditioned at 4 phase points.
2) Total time of conditioning was about 30 hours (all phases).
3) Couplers can be conditioning at all phase points to vacuum level P < 1E-6 Torr, which allows to work at full power without HV bias,
4) At some reflected phase points MP does not disappear completely. Some small activity still exists. When HV bias +3kV is applied vacuum becomes better (for example from 7E-7 to 2E-7)
5) Place of MP is not known. It can be ceramic window, connecting chamber, etc.

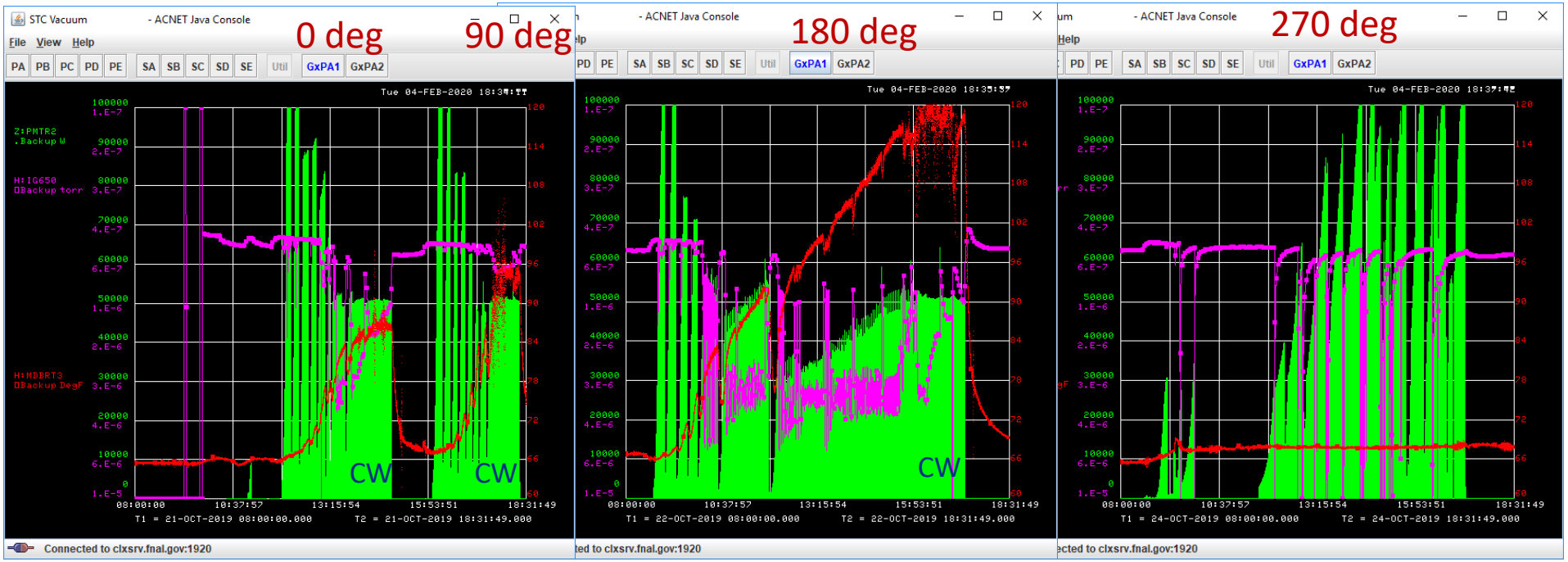
Testing with baseline warm parts (SS tubes and bellows, copper plated inner and outer conductors)



Two EM-shielded couplers were re-assembled with baseline warm parts:
Some extra-reflection in the coupler chain (most likely bridge geometry change)

Test with nominal warm parts (SS copper plated tubes/bellows)

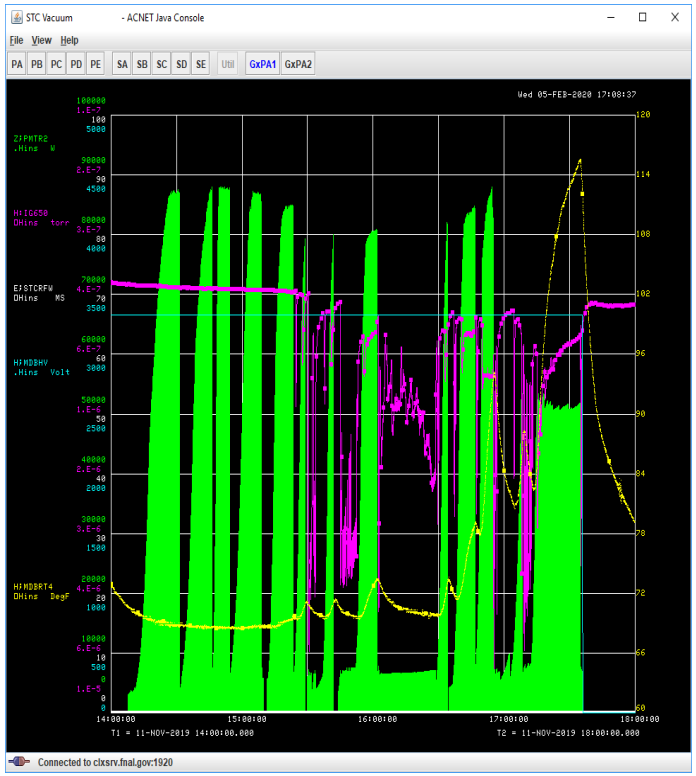
With nominal warm parts coupler tested with bias (OK), then were conditioned w/o bias. More conditioning required for 180 deg and 270 deg reflection phases



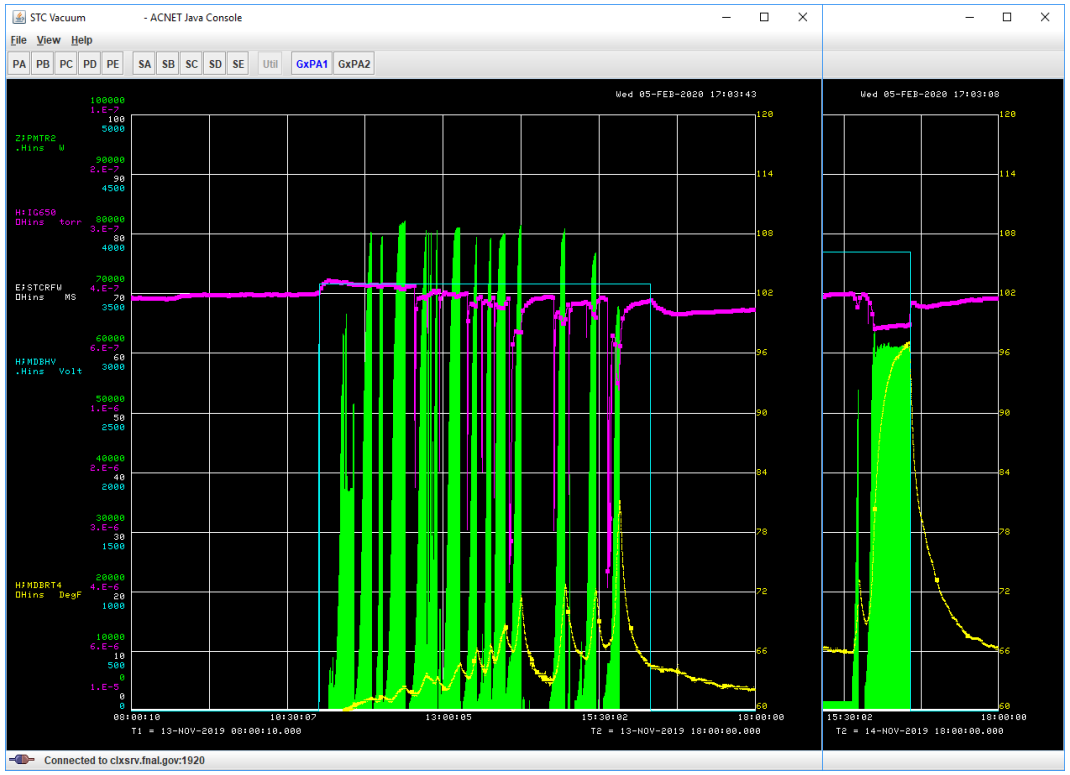
- no MP activity, fast processing for 0°; 90°, sign of MP at 180°, more activity at 270°.
- 270 deg phase after processing was used for “Memory test”

Memory test (without HV bias):

Goal: After RF processing w/o HV bias for 270 deg (worst case), then fill system with dry nitrogen, pump it again and check if coupler remember processing



Nov.12 - Fill with 1bar Nitrogen for 2hrs



Test before Nitrogen infusion,
no MP activity, incl. 50kW CW

After N infusion;
Test up to 60kW 500ms, no bias, no MP

Conclusion: coupler remember rf processing after exposition to nitrogen

Summary

Conventional design:

- With modifications done after 1st test couplers reached required CW power level w/o MP after short processing (DC bias +4.5kV)

EM shielded design:

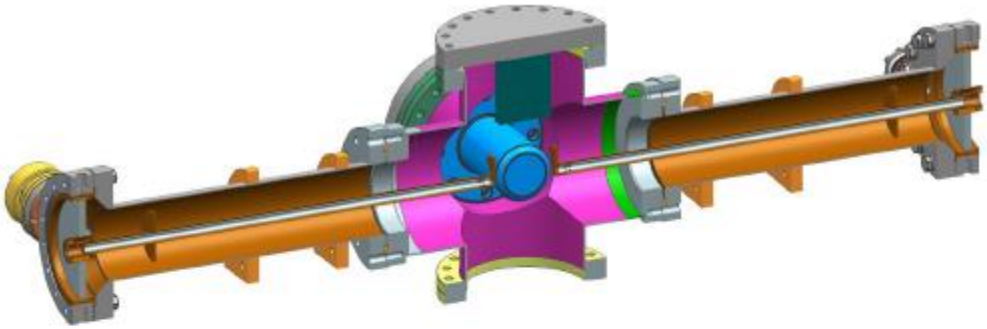
- 50kW CW power level was achieved after short processing for each reflection phase.
- Repeated for nominal configuration of warm part

Finally both couplers were qualified at 50kW full reflection at arbitrary reflection phase.

Extra tests (EM-shielded design)

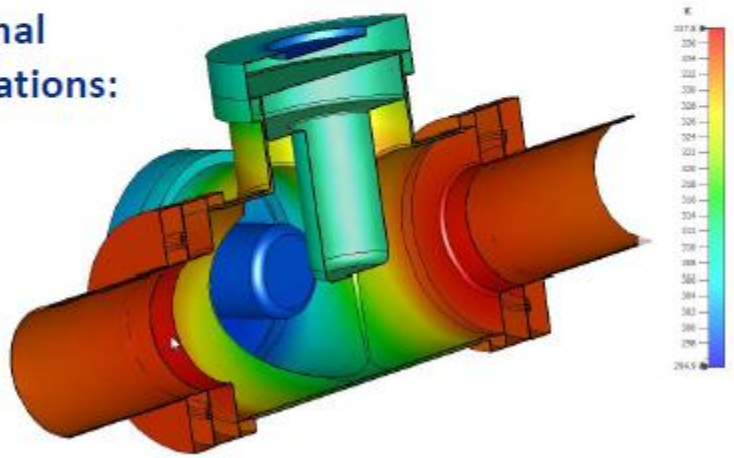
- **HP processing without bias successfully demonstrated (~30hrs for all phases).**
- **Waveguide heating was measured. Temperature is high, Standard WR1150 was proposed to reduce power heating (current design)**
- **"Memory Test" to demonstrate that coupler remember RF processing w/o bias after explosion on dry nitrogen for several days. Yes it works.**

New vacuum chamber of the test stand with capacitive coupling

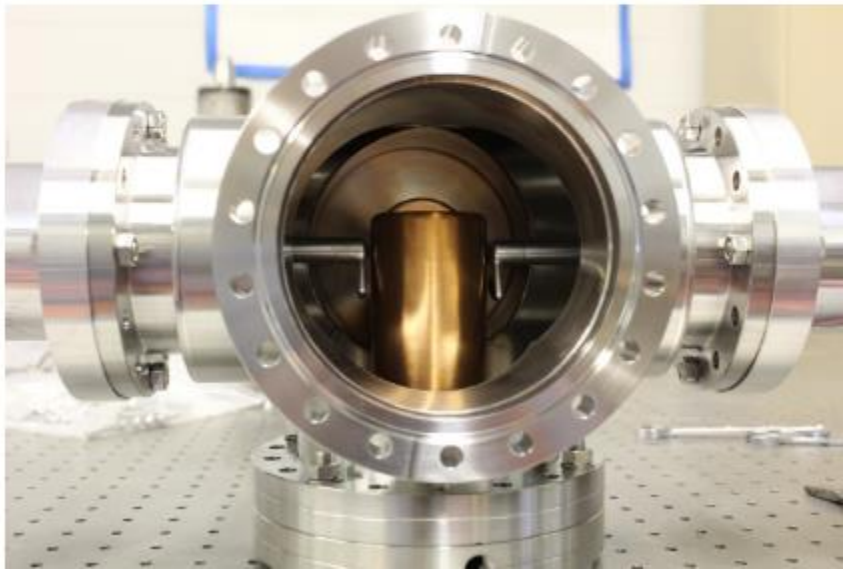


New chamber with dummy couplers:

Thermal simulations:



Max. T < 60C for 50 kW, CW, full reflection



Other upcoming test stand upgrades: Pumping station with better pumping rate, water cooling manifold for strap connections

Thank you

Coupler Incoming Inspection (QC) at FNAL

- Incoming inspection will be governed by a Vector traveler which will be developed prior to receipt of couplers
- Will rely in part on vendor supplied QA/QC documentation
  - Vendor will follow QA plan that developed and approved at initiation of contract
  - Similar to plan followed for LCLS-II coupler procurement
- Areas covered in the incoming QC at FNAL are:
  - Documentation completeness
  - Component completeness (are all the parts there?)
  - Visual inspection
  - Leak check
  - Dimensional inspection reports review
  - RGA and bakeout results
  - Cleanliness